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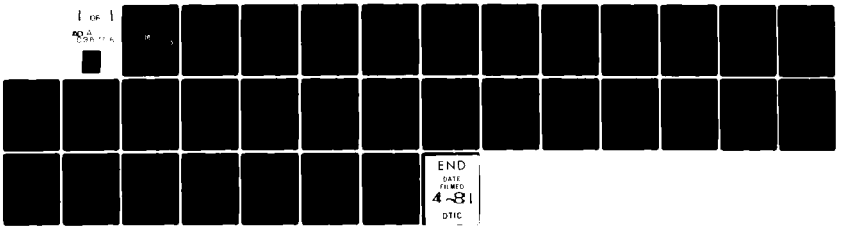

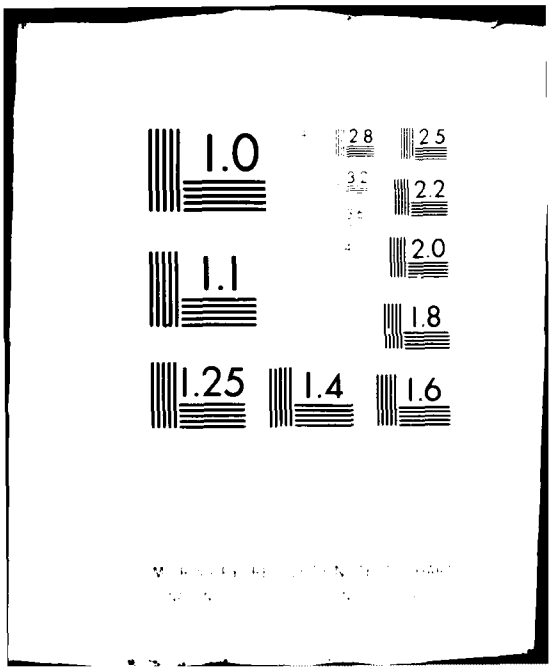
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of the research reported here was to develop a specification method for the specification of abstract data types and an access control facility suitable for inclusion in high-level programming languages. The research was not intended to include the design of a complete language but instead involved the development of programming language features that aid in the development of languages designed for producing reliable software. A constructive specification method was developed for specifying abstract data types. Abstract data types

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20. ABSTRACT CONTINUED

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Data Structure Definition and Access Control Facilities for Languages Designed for the Development of Reliable Software

University of South Carolina

October 20, 1979 - October 19, 1980

Billy G. Claybrook

Principal Investigator

1.0 Introduction

The concept of abstraction has become an important part of problem solving and in particular software development. Through the use of abstract data types, programs can be written that manipulate objects of a given type without being concerned with how the primitive operations on the objects are implemented.

In this paper we describe a constructive (or operational) specification method for specifying abstract data types. We limit our discussion to the specification of data abstractions and do not treat procedural abstractions. A constructive method specifies how a type's operations affect instances of the type. By this definition, the abstract model ([BERZV79]) approach can be considered a constructive specification method while the algebraic method ([GUTTJ75], [GOGUJ78]) is nonconstructive.

The work described in this paper includes some important changes in notation to the constructive specification method described by the author in [CLAYB79] and [CLAYB80]. The improvements in notation permit more concise and more readable specifications to be written. This paper gives a more detailed description of the method, especially with respect to proofs of implementation correctness.

This paper is organized as follows. In the next section we present some preliminary concepts dealing with the algebraic and abstract model specification methods. In Section 3 we describe the constructive specification method by specifying stack, mapping and symboltable data types. Then in Sections 4 and 5, we discuss implementing and proving implementation correctness for abstract data types specified constructively using the symboltable data type. The symboltable data type example was chosen because it is a nontrivial example and because the reader can readily compare the constructive specification given for it in this paper with Guttag's algebraic

Problem Studied

The proposed research was to develop a specification method for the specification of abstract data types and an access control facility suitable for inclusion in high-level programming languages. The research was not intended to include the design of a complete language but instead involved the development of programming language features that aid in the development of languages designed for producing reliable software.

Results of the Research

To meet the objectives of this research, a constructive specification method was developed for specifying abstract data types. Abstract data types are specified using the module encapsulation mechanism. A constructive specification consists of two parts: a logical structure specification and a semantics of operations specification. *The constructive specification method* is described in the following pages.

specification (in [GUTTJ78]). In Section 6 we treat a database view as a data abstraction and realize it as an abstract data type and specify it using the constructive specification method. This particular example differs from the other data types specified in this paper because the representation data is shared by all instances of the database view. In addition, it illustrates at least one important difference between the constructive method and the algebraic method. Finally, in Section 7 we present a rather detailed comparison of specification methods.

2.0 Preliminaries

An abstract data type can be viewed as a set of values (or objects) and a set of operations applicable to the values. The definition of an abstract data type consists of a specification of the type and an implementation of the type. A specification of a type is a representation-independent description of all properties of the type. This includes specifying the syntax and semantics of a set of primitive operations applicable to the type. The implementation of a type involves assigning a representation for the set of objects defined and then implementing the type's primitive operations on the representation selected. A stack data type, for example, is often represented by a vector and the stack operations, e.g. push, pop, etc., are implemented using the vector and its operations. In turn, the vector type itself has a representation, such as a contiguous block of memory cells, and a set of operations implemented in terms of this representation.

A substantial amount of work has been done to develop specification methods and languages. These approaches to specification have usually been classified as algebraic specifications ([ZILLS75], [GUTTJ78], [GOUGJ78]) and abstract model specifications ([BERZV79], [WULFW76], [HOARA72]). Each approach has its advantages and disadvantages ([GUTTJ78], [BERZV79]).

Presently, the most popular method for specifying abstract data types is the algebraic specification method. The reason for this appears to be

twofold: (1) the algebraic method has a mathematical basis in algebra and has been formalized, and (2) the algebraic method has been widely publicized.

When an abstract data type is specified algebraically, it is viewed as an algebra. One then writes the syntax of the operations and the axioms of the corresponding algebra. The syntax specification defines the names, domains and ranges of the type's primitive operations. Writing the axioms is considered to be the semantic specification. The axioms are written in the form of equations (or rewrite rules) which relate the primitive operations of the type to each other. To prove implementation correctness, one must show that an implementation satisfies all the axioms.

With the abstract model approach, an abstract representation (or abstract object) is selected for objects of the type being defined. It is important that the users of a type know what its abstract representation is since the semantics of the type's operations are specified with respect to the abstract representation. For example, the abstract representation of a stack is usually a mathematical sequence. The syntax of a type's operations is defined just as it is in the algebraic approach. The difference between these two methods involves specification of the semantics of operations. The semantics of a type's operations are specified by specifying how each of the operations affects the abstract object (some operations such as membership and retrieval operations do not change the state of the abstract object.) This essentially means that to specify the semantics of a type's operations we specify how the operations affect an instance of the type. To prove implementation correctness, the implementation of each individual operation is proven correct (with respect to the semantics specified for it). It is noteworthy to point out here that an abstract object's operations are used only in specifying the semantics of a type's operations and are not used in implementing the type.

It is important that abstract data types be specified using a formal specification language for at least three reasons:

1) communicating the properties of a type in a precise and unambiguous manner,

2) proving implementation correctness, and

3) designing abstractions.

Communication of properties in a clear and concise manner is important because this permits a type to be understood by both the user of the type and the implementer of the type. Proving implementation correctness, though often nontrivial, should be done when it is an important aspect of software development for an organization using the resulting software. For instance, several governmental agencies believe that trusted software, i.e. verified software, is important for security reasons. Formal specification as an aid to the design of data abstractions may be the most important reason for doing the specification. From our experience in realizing data abstractions ranging from simple abstractions such as stacks to more complex abstractions such as database views, formally specifying an abstraction usually leads to a "better" and often simpler abstraction. With the exception of a few cases such as the one just mentioned, ease of demonstrating consistency of specifications and implementations is often of lesser importance than ease of examinining and manipulating specifications.

3.0 The Constructive Specification Method

As stated above, a complete definition of an abstract data type consists of a specification of the type and an implementation of the type. Specification details are visible to a programmer while implementation details are hidden from programmer use. We will use the module encapsulation mechanism described in [CLAY880] to define abstract data types.

The constructive specification of an abstract data type consists of two parts: a logical structure specification and an operation specification. Each of these specifications is discussed in detail below.

3.1 The logical structure specification

When a programmer specifies an abstract data type, he usually has some preconceived notions about the data abstraction such as what an instance "looks like" (independent of any concrete representation), relationship(s), if any, between constituent objects, etc. (an instance of a type consists of a collection of constituent objects). In the constructive approach, these notions are communicated to the user and implementer of a type via a logical structure specification. These notions tend to make understanding a type easier and hence aid in communicating properties of a type. A logical structure specification essentially defines an abstract model of the type being specified. It does this by defining relationship(s), if any, between constituent objects, by defining restrictions to the relationship(s), and by expressing an instance of the type as a tuple of elements. The elements of such a tuple may be sets of constituent objects and relationship(s).

A logical structure specification does not specify an abstract data type; however, it is an important part of the specification of a type because the semantics of operations are specified in terms of how they affect an instance of the type.

The unbounded stack data type in Figure 1 illustrates the various parts of a logical structure specification. The objects section contains the names of the types of constituent objects. Constituent object types can be defined within a logical structure specification (see Figures 2 and 3) or they can be passed as parameter(s) to a defining module (see Figure 1). The relationships section defines any relationship(s) that may exist between constituent objects.

```
module mapping[domaintype: Type, rangetype: Type];
    logical structure
        objects
            type NODE = record NAME: domaintype;
                               ATTRIB: rangetype
                        end;
            occurrence <M: collection NODE>
    operations
        syntax
            NEWMAP: ⟶ mapping
            defmap: mapping x domaintype x rangetype ⟶ mapping
            evmap: mapping x domaintype ⟶ rangetype ∪ {UNDEFINED}
            isdefined: mapping x domaintype ⟶ boolean
        semantics
            ID: domaintype; ATTRLIST: rangetype; m: mapping;
            NEWMAP = ∅;

            evmap(m,ID) = if ∃ x ∈ m ➔ x.NAME = ID
                then x.ATTRIB else UNDEFINED;

            isdefined(m, ID) = if ∃ x ∈ m ➔ x.NAME = ID
                then TRUE else FALSE;

            defmap(m, ID, ATTRLIST) = m ∪ { x with [NAME = ID,
                 ATTRIB = ATTRLIST] } ;
end mapping;
```

Figure 2. Constructive specification of mapping data type

```
module stack[elementtype: Type];

    logical structure
        object ELEM: elementtype
        relationships ONTOPOF: ELEM to ELEM
        occurrence  ⟨S: collection ELEM, O: ONTOPOF⟩
        invariant assertions
            1. ONTOPOF is linear

    operations
        syntax
            NEWSTACK: ⟶ stack
            push: stack x elementtype ⟶ stack
            pop: stack ⟶ stack
            top: stack ⟶ elementtype ∪ {UNDEFINED}
            replace: stack x elementtype ⟶ stack ∪ {ERROR}

        semantics
            x, y, z: elementtype; s: stack;
            NEWSTACK = ⟨∅, ∅⟩

            push(s, x) = s with [S = S ∪ {x} , O = if
                s = NEWSTACK then ∅ else O ∪{⟨x, top(s)⟩}]

            pop(s) = if S = ∅ then NEWSTACK
                else s with [S = S - {x} , O = O - {⟨x, y⟩|
                    ⟨x, y⟩∈O ]  where x = top(s)

            top(s) = if s = NEWSTACK then UNDEFINED else x
                where x∈ S and ( ∄ y∈ S) ( ⟨y, x⟩∈ O)

            replace(s, x) = if s = NEWSTACK then ERROR
                else s with [S = (S - {y} ) ∪ {x} ,
                    O = (O - ⟨y,z⟩ ) ∪{⟨x, z⟩ }]
                    where y = top(s)
end stack;
```

Figure 1. Constructive specification of unbounded stack type

```
module symboltable[domaintype: Type, rangetype: Type];

    logical structure
        objects
            type NODE = record NAME: domaintype;
                               ATTRIB: rangetype
                        end;
            type BLOCK = record CONTENTS: collection NODE; end;
        relationships NESTED: BLOCK to BLOCK
        occurrence <N: collection NODE,
            B: collection BLOCK, ND: NESTED>
        invariant assertions
            1. NESTED is linear
            2. ∃ b ∈ B ➔ <b, b'> ∈ ND ∀ b' ∈ B

    operations
        syntax
            INIT: ⟶ symboltable
           *currentblock: symboltable ⟶ BLOCK
            enterblock: symboltable ⟶ symboltable
            leaveblock: symboltable ⟶ symboltable
            isinblock: symboltable x domaintype ⟶ boolean
            retrieve: symboltable x domaintype ⟶ rangetype
            addid: symboltable x domaintype x rangetype ⟶
                                                symboltable

        semantics
            b, b1, cb: BLOCK; x: NODE; ID: domaintype;
            ATTRLIST: rangetype; s: symboltable;

            INIT = s with [N = ∅, B = {b with [b.CONTENTS =
                   ∅]}, ND = ∅];

            currentblock(s) = b where ∄b1 ∈ B ➔ <b1, b> ∈ ND;

            enterblock(s) = s with [B ∪{b with [CONTENTS = ∅ ]},
                    ND = ND ∪{ <b, cb> } ] where b ∉ B;

            leaveblock(s) = if ND = ∅ then INIT
                            else S with [N = N - {cb.CONTENTS},
                              B = B - {cb},
                              ND = ND - {<cb, b> | <cb, b> ∈ ND}];

            isinblock(s, ID) = if ∃ x ∈ cb.CONTENTS ➔ x.NAME = ID
                    then TRUE else FALSE;

            retrieve(s,ID) = if s = INIT then UNDEFINED
                    else if ∃ x ∈ cb.CONTENTS ➔ x.NAME = ID
                         then x.ATTRIB
                         else retrieve(leaveblock(s), ID);

            addid(s, ID, ATTRLIST) = s with [N = N ∪{ x with
                    [NAME = ID, ATTRIB = ATTRLIST]},
                    B = B with [cb.CONTENTS = cb.CONTENTS ∪{x}]];
end symboltable;
```

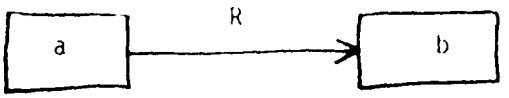
Figure 3. Constructive specification of symboltable data type

Possibly the most important ingredient of a logical structure specification is the invariant assertion. The primary functions of the invariant assertion are to specify restrictions to relationships and to specify assertions about the model on which the semantics of operations are specified. When the semantics of operations are specified, care must be taken to ensure that the operations do not "violate" or "ignore" any of the assertions.

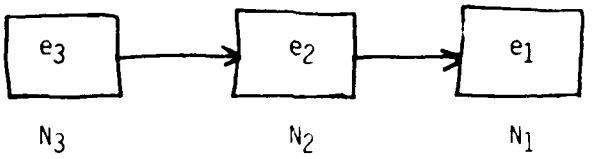
The abstract data types specified in this paper do not reflect the true importance of the invariant assertions. Invariant assertions are particularly valuable in specifying abstract data types where there are several relationships between constituent objects and there are important restrictions to these relationships. For example, in specifying database views there are usually several relationships between entity types. As an example, a specification of the presidential database described in [TAYLR76] required 26 invariant assertions. In this context, a logical structure specification is analoguous to a database subschema definition. However, there is an important difference betweeen a logical structure specification and say a CODASYL subschema definition. The invariant assertions of a logical structure specification define the semantics of the relationships between entity types. A CODASYL subschema definition can only define the syntax of the relationships and not the semantics.

Wyckoff ([WYCKM80]) has suggested the use of diagrams to pictorially describe data types specified using the constructive approach. These diagrams can be used to aid in the specification of a data type or by a user and an implementer to help them understand the type. A diagram can be drawn directly from a logical structure specification. Diagrams for the stack, mapping and symboltable data types are shown in Figure 4. As we will see, the diagrams in Figure 4 aid us in developing and understanding the correspondence function

given in Figure 6. In these diagrams a R b, i.e. object a is related to object b via relation R, is represented as

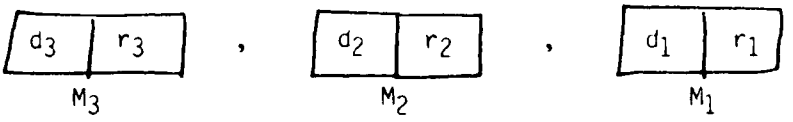


To take a closer look at logical structure specifications, we examine the unbounded stack data type and the symboltable data type in Figures 1 and 3, respectively. The stack type is a parameterized type with the type of elements in a stack instance passed as a parameter. An instance of the stack type consists of a collection of objects of type elementtype. The relationship between the elements of the stack is ONTOPOF; ONTOPOF is linear ([CLAY879] provides a list of terms, such as linear, is ordered on, etc., that expedite writing invariant assertions.) The terms used in this paper should be self explanatory.



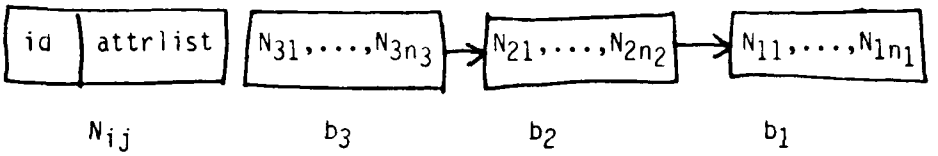
N_i: NODE, e_i: elementtype;
ONTOPOF = $\{\langle N_3, N_2\rangle, \langle N_2, N_1\rangle\}$

4(a) diagram of stack data type



M_i: NODE; d_i: domaintype; r_i: rangetype;

4(b) diagram of mapping data type



N_{ij}: NODE; b_i: BLOCK; id: domaintype; attrlist: rangetype;

NESTED = $\{\langle b_3, b_2\rangle, \langle b_2, b_1\rangle\}$

4(c) diagram of symboltable data type

Figure 4. Diagrams of stack, mapping and symboltable data types

Constituent objects of a symbol table consist of instances of BLOCK and NODE. These object types are defined within module symboltable; however, the types of the component elements of NODE are passed as parameters. The relationships and occurrence sections need no explanation; however, the invariant assertions section does require some explanation. Assertion 2 states that there is a block which is assumed to be global to all blocks in a program. This same assumption is made in Guttag's specification of the symboltable data type ([GUTTJ78]) but it is not explicitly stated.

3.2 Specification of operations

The operations section consists of two parts: a syntax specification and a semantics specification. The syntax section defines the names, domains and ranges of a type's primitive operations. Hidden (or auxiliary) operations, i.e. operations that are used in specifying other operations but are not available for programmer use, are indicated by placing an asterisk ('*') to the left of their name. Operation currentblock in Figure 3 is an example of a hidden operation.

In many cases, specifying the semantics of a set of operations using the constructive approach is straightforward. With respect to the symboltable data type in Figure 3, the INIT operation creates a symbol table and establishes the outermost scope. Operation enterblock establishes a new block nested in the current block and leaveblock removes the current innermost block. Operation isinblock tests whether or not an identifier has been declared in the current block and retrieve retrieves the attribute list of an identifier from the block closest to the innermost block. Operation addid is explained by the following example. The symbol table for the program shown in Figure 5 at the point of compilation indicated by the arrow is given by

addid(addid(enterblock(addid(init, x, real)), x, complex), y, complex).

```
begin
    x:  real;
          .
          .
          .
    begin
        x, y:  complex;
                 .
                 .
                 .
    end
           .
           .
           .
end
```

Figure 5. Program segment

4.0 Implementation of Abstract Data Types

An implementation of an abstract data type using the constructive specification method consists of a representation specification followed by an implementation of the type's operations with respect to the representation. The representation specification of an abstract data type indicates the concrete object(s) used to represent the type and the correspondence between an abstract object and its concrete object(s). Correspondence is defined as a function from concrete object(s) to an abstract object. The correspondence function is a homorphism and it is identical in functionality to the abstraction function of Hoare ([HOAR72]). A correspondence function is named and it is used in proofs of implementation correctness.

A correspondence function may be relatively simple (as it is for the symboltable data type and its representation) or it may be quite complex. In general, the more dissimilar the concrete objects and the abstract values they represent, the more complex the correspondence function.

The correspondence function for the implementation of the symboltable data type in Figure 6 is SYMT. The concrete objects in this case are instances of the stack and mapping data types specified in Figures 2 and 3, respectively. SYMT maps these concrete objects into a symbol table. The occurrence tuple shown in Figure 6 represents an occurrence of symboltable where N = $\bigcup$M, B = S and ND = 0. M is defined in Figure 2 and S and 0 are defined in Figure 1. This definition of SYMT can be easily understood by looking at Figure 4. Implicit in the definition of SYMT is the fact that a block is equivalent to an element of a stack and each element of a stack is a collection of mappings.

The implementation section provides an implementation of an abstract data type's operations in terms of concrete object(s) and concrete object

operations. An implementation of an operation is specified using composition of operations, tests for equality (or inequality) and the if-then-else construct. An implementation of the symboltable data type is given in Figure 6.

```
representation

    symtab: symboltable; stk: stack; m: mapping;
    symtab = SYMT(stk(m)) where SYMT(stk(m)) = <UM, S, 0>

implementation
    stk: stack; id: domaintype; attr: rangetype;

    INIT = SYMT(push(NEWSTACK, NEWMAP))

    enterblock(SYMT(stk)) = SYMT(push(stk, NEWMAP))

    addid(SYMT(stk), id, attr) =
            SYMT(replace(stk, defmap(top stk), id, attr)))

    leaveblock(SYMT(stk)) = if 0 = ∅ then
                            SYMT(push(NEWSTACK, NEWMAP))
                            else SYMT(pop(stk))

    retrieve(SYMT(stk), id) = if stk = push(NEWSTACK, NEWMAP)
                              then UNDEFINED
                              else
                               if isdefined(top(stk), id)
                                then evmap(top(stk), id)
                                else retrieve(leaveblock(
                                      SYMT(stk)), id)

    isinblock(SYMT(stk), id) = isdefined(top(stk), id)

    currentblock(SYMT(stk)) = top(stk)
```

Figure 6. A representation and an implementation of symboltable data type

5.0 Proving Implementation Correctness

For the constructive specification method, a proof of implementation correctness involves showing that the implementation of each individual operation is correct with respect to a correspondence function. That is, for the symboltable data type we must show the following:

for each symboltable operation σ show that

σ(SYMT) = SYMT(σ'), where σ' is an

implementation of σ .

A pictorial view of SYMT is given in Figure 7 using the implementation of symboltable operation addid. This pictorial description suggests that proving implementation correctness involves showing that the instance resulting from the left side of each operation implementation (given in Figure 6) is the same as the instance resulting from the corresponding right side.

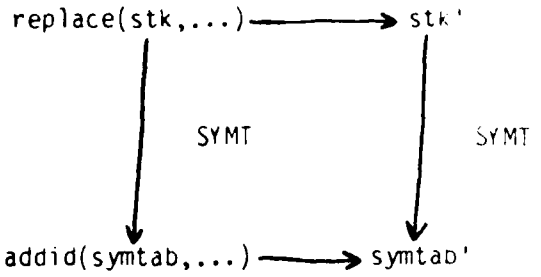


Figure 7. Pictorial meaning of addid(SYMT) = SYMT(replace)

Before a proof of implementation correctness can be done for the symboltable data type, it is necessary to prove an implementation invariant. In general, an implementation invariant is a property that is true for all values of a type produced by an implementation of the type. An implementation invariant comes up as one proceeds through a proof of correctness. They make themselves obvious when the rewrite process during a proof can no longer continue. In general, one may not know all the implementation invariants when a proof is initiated.

For the symboltable, the following implementation invariant, posed as a theorem, must be proven:

for each symboltable = SYMT(stk), stk $\neq$ NEWSTACK.

To prove the theorem, we must show that the invariant is true for all symboltable operations that produce symboltable values. Since INIT, enterblock, addid, and leaveblock are the symboltable operations that produce

Proof

right side

SYMT(push(stk, NEWMAP))

= SYMT(stk with [S = S ∪ {NEWMAP} , O = if stk = NEWSTACK
then ∅ else O ∪ {<NEWMAP, top(stk)>}]
(by semantics of push)

= SYMT(stk with [S = S ∪ {NEWMAP} , O = O ∪ {<NEWMAP,
top(stk)>}]
(by implementation invariant)

= symtab with [B = B ∪ {b with [CONTENTS = {NEWMAP}]},
ND = ND ∪ {<b, cb>}]
(by correspondence function SYMT in Figure 5)

left side

enterblock(SYMT(stk)) = enterblock(symtab)
(by definition of SYMT)

= symtab with [B ∪ {b with [CONTENTS = ∅]},
ND = ND ∪ {<b, cb>}] where b ∉ B
(by semantics of enterblock)

The left and right sides are equal since NEWMAP = ∅ .

Figure 9. Proof of implementation correctness for operation enterblock

5.1 *Comments on proofs of implementation correctness*

Proofs of implementation correctness for types specified using the constructive approach are relatively straightforward. For the constructive specification of the symboltable data type the degree of difficulty for a proof of implementation correctness is about the same as for Guttag's algebraic specification (see [GUTTJ78]). The proof of implementation correctness for the symboltable implementation given in Figure 6 is relatively simple since the representation and instances of the type are very similar in nature. When the representation of a type and instances of the type are dissimilar, in general, the proofs become more difficult. For example, we specified an ordered linear list (using both the algebraic specification

symboltable values, it suffices to show that given a stack, stk, for which the invariant is true, each of these operations produces a new stack for which the invariant is still true. Thus, we will have shown inductively that the invariant is true for all values of the symboltable type. Wyckoff (WYCKOFF) gives a complete proof of the invariant; we repeat only the proof involving operation addid (see Figure 8).

addid(SYMT(stk), id, attr) = SYMT(replace(stk, defmap(top(stk), id, attr)))
(by implementation of operation addid)

= SYMT(stk) since stk ≠ NEWSTACK by hypothesis and letting
d = defmap(top(stk), id, attr)

= SYMT(stk with S = (S - {y}) ∪ {d}, U = (U - ⟨y, z⟩) ∪ {⟨d, z⟩}, where y = top(stk))
(by semantics of replace)

= SYMT(stk') where stk' ≠ NEWSTACK

Therefore the invariant is true for operation addid.

Figure 8. Proof of the implementation invariant using operation addid.

A complete proof of implementation correctness for the implementation given in Figure 6 is given by Wyckoff. To illustrate our proof procedure, we repeat only a proof of implementation correctness for operation enterblock (see Figure 9). The other proofs are similar. In Figure 9 we show

enterblock(SYMT(stk)) = SYMT(push(stk, NEWMAP))

by showing that the instances resulting from the left and right sides are identical.

The development of the right side in Figure 9 makes use of the semantics of stack operation push, the implementation invariant defined above, the function SYMT, and the fact that cb = top(stk). The development of the left side is simpler and makes use of the semantics of operation enterblock and SYMT.

method and the constructive method) and then implemented it using a binary search tree. In our attempts to complete a proof of implementation correctness for the list, we had to consider several special cases of the binary search tree for both specifications. For the algebraic specification, considerable ingenuity was required as well as proving some auxiliary theorems to permit rewriting to continue during proofs (see [CLAYB81b]). Like the proofs for the algebraic specification of the linear list, the proofs for the constructive specification were relatively long; however, they were straightforward in comparison.

6.0 A Database View Example

In this section we realize a database view an an abstract data type and specify it using the constructive specification method. This example is included because database views are substantially different than the other data abstractions specified in this paper. The difference exists because databases are normally shared data objects with many different users capable of updating the database and the updates may affect the values of a view.

A database view is an abstraction of an underlying database. A view has the following properties:

1) an underlying database is assumed to exist; otherwise, it is impossible to derive a view,
2) views are not materialized, i.e. they are not stored in a database, and
3) in a shared database environment, some values of a view may be created by other users who are updating the underlying database.

An underlying database is considered to be the representation of a database view and an implementation of a database view is an implementation of the view's operations with respect to the underlying database.

In the example described below, the database view specified is a relational view ([DATEC77]). For simplicity, we assume that the view consists of a single relation (referred to as a view relation) and the representation is a single relation (referred to as a base relation) stored in the database. The base relation consists of a set of tuples with the following attributes

(car_no, model, body_no, yr, current_value, mi, disp, dest, rc, col, loc)

while an instance of the view relation consists of a set of tuples with the following attributes

(car_no, mi, dest, disp, rc)

Each car owned by the car rental company (described below) has a tuple corresponding to it stored in the database with car_no being a primary key.

The environment for this example is as follows. A car rental company in a large city has a central headquarters where car purchases are made, allocations of cars to local rental offices are made, etc. When a new car is purchased, all information on the car such as license plate number (car_no), body identification number, color, model, etc. are stored in the database by headquarters database system personnel. When a car is assigned to a local rental office, the value of the location attribute of the particular car's tuple is set to the location of the local office to which it is assigned and its disposition (disp) is set to 'avail', meaning that it is available to be rented.

The function of a local rental office differs from that of the headquarters. A rental office does not need access to all of the information in a car tuple. For this reason, a local office's database consists of a set of the view relation tuples described above. A local office can apply the operations rent_car, return_car, maint_car, return_maint, and avail_car to its database represented by its view. Operations rent_car and return_car are used when a car is rented and returned, respectively. Operations maint_car and return_maint are used when a car is sent to maintenance and returned from

maintenance, respectively. Operation avail_car is used to obtain a set of available cars having a specified rate class. The rental car database view described here is a simplified version of a view described in [CLAYB81a]. In the description of the view in [CLAYB81a], the view also has rental car history and maintenance history view relations.

The database view is realized as the abstract data type dbview and specified using the constructive specification method (see Figure 10). In this specification we assume that the data types car_number, mileage, etc. are available for use in module dbview. Type re_set is defined as a set of car numbers. Type dbview is a parameterized type, with parameter xloc (the value of xloc is a local rental office location). A particular instance of dbview is a set of tuples consisting of only those cars assigned to a particular local rental office. For this reason the local office location does not have to be specified as a parameter in each of dbview's operations.

```
module dbview(xloc: location);
    logical structure
        objects
            type TUPLE = record  ca: car_number;
                                 mi: mileage;
                                 dest: destination;
                                 disp: disposition;
                                 rc: rate_class
                               end;
            occurrence      <collection TUPLE>

    operations
        syntax
            rent_car: dbview x car_number x destination → dbview ∪
                                                          {UNDEFINED}
            return_car: dbview x car_number x mileage → dbview ∪
                                                        {ERROR}
            maint_car: dbview x car_number → dbview ∪ {ERROR}
            return_maint: dbview x car_number → dbview ∪{ERROR}
            avail_car: dbview x rate_class → rc_set

        semantics
            c: car_number; d: destination; m: mileage;
            r: rate_class; t: TUPLE; db: dbview;
            rent_car(db, c, d) =
                if ∃t ∈ db → (t.ca = c and t.disp = 'avail')
                 then db with [t.disp = 'rented, t.dest = d]
                 else UNDEFINED;

            return_car(db, c, m) =
                if ∃t ∈ db → (t.ca = c and t.disp = 'rented')
                 then db with [t.disp = 'avail', t.mi = m]
                 else ERROR;

            maint_car(db, c) =
                if ∃t ∈ db → (t.ca = c and t.disp = 'avail')
                 then db with [t.disp = 'maint'] else ERROR;

            return_maint(db, c) =
                if ∃t ∈ db → (t.ca = c and t.disp = 'maint')
                 then db with [t.disp = 'avail'] else ERROR;

            avail_car(db, r) = {t.ca | t ∈ db and t.rc = r and
                 t.disp = 'avail'};
end dbview;
```

Figure 10. Constructive specification of a relational database view

A representation of dbview is given in Figure 11. In this representation specification, the correspondence function VIEWMAP is defined as a derivation of view relation tuples from base relation tuples. This is a natural way to define correspondence functions for relational database views and has been adopted in RIGEL ([ROWE79]) and in EXT_Pascal ([CLAYB81a]).

```
representation
     db:  dbview;
     db = VIEWMAP(R) where
          VIEWMAP(R) = {<r.ca, r.mi, r.dest, r.disp, r.rc> |
                        r∈R and r.loc = xloc}
```

Figure 11. A representation for view dbview

The function VIEWMAP defines an instance of dbview as consisting of a set of tuples having the five attributes: ca, mi, dest, disp, and rc. R is the representation of instances of dbview and it is the base relation from which instances of dbview are derived.

An implementation of dbview's operations is omitted here but they would be implemented in terms of R's operations, namely append, delete and replace. The interested reader should see [CLAYB81b] for an implementation of dbview and a proof of implementation correctness for some of dbview's operations.

6.1 Comments on the database view example

The database view example was included in this paper for two reasons; (1) to show the utility of the constructive specification method, and (2) to serve as an example for comparison with the algebraic specification method in an environment where sharing of representation data occurs.

In the database view example, values of an instance of dbview may be created by the headquarters database personnel. For example, a car tuple may be removed from a view if the location of the car is modified, i.e. the car is assigned elsewhere or sold, by headquarters personnel, or the headquarters may decide to alter the rate_class of some or all of its cars.

Specifying data abstractions in which representation data is shared causes no particular problems for the constructive specification; however, it does cause some problems for the algebraic method. The reason for this is that with the algebraic method, the behavior of an object and the generation of that object are intertwined. The problem incurred by the algebraic method is that some of the constructor operations that create values of dbview are

not in dbview's operation set but instead are included in the underlying database's operation set. With the algebraic specification, all values of an abstract data type must be produced by some sequence of constructors. To specify dbview algebraically, we have to include the auxiliary (or hidden) operations emptyview and add_car. Claybrook ([CLAYB81b]) provides a complete specification of dbview using Guttag's algebraic specification method. The specification requires 12 axioms.

7.0 Comparison of Specification Methods

Below we summarize properties and characteristics of constructive and algebraic specification methods. Each method appears to have some inherent problems that are difficult to handle. It may seem that we are overly criticizing the algebraic specification method. However, one of the problems in comparing these two methods is that the algebraic method has been examined and researched by more people than the constructive method and thus more is known about its strengths and weaknesses.

In the algebraic approach, a data type is specified by giving a set of axioms relating the type's primitive operations. For the constructive specification, the logical structure of a type is specified, thus defining an abstract model of the type, and the operations are specified with respect to this model. With the abstract model approach, an abstract object such as a sequence or set is selected and the type's primitive operations are specified with respect to the abstract object. The constructive specification method described in this paper is very similar to the abstract model approach; therefore, any comments made about one applies to the other.

Algebraic specifications are usually considered to be more elegant than specifications developed using a constructive method. If we do not consider hidden operations as unnecessary detail then the algebraic method does not introduce unnecessary detail. Since it has a mathematical basis in algebra, it is well suited to formal analysis and has been used as the basis for

"semi-automatic" verification systems such as AFFIRM ([MUSSD79]). Another feature of the algebraic specification method is that it is compact; however, as we shall see below, algebraic specifications are not always compact.

Several authors ([FLONL79], [BERZV79], [MAJSM79]) have pointed out some serious problems with algebraic specifications. These problems are for the most part inherent in the basic methodology used to develop the method and, thus, are difficult to remedy. Fortunately, most of these problems are not problems for the constructive methods. Majster ([MAJSM79]) states that one of the problems with algebraic specifications is the necessity to introduce hidden or auxiliary operations for some specifications. These operations are not harmful from a theoretical point of view but they do cause two problems. The number of auxiliary operations can become quite large and the number of axioms may increase sharply (especially if some of the auxiliary operations must be constructors). Majster performed a case study for the description of a file with nine (9) operations and 10 auxiliary operations and ended up with over 50 axioms. One of the claimed benefits of algebraic specifications, compactness, was lost in this specification. Another problem is that the auxiliary operations have to be implemented.

Another major problem with algebraic specifications involves producing a well-formed specification, i.e. producing a complete and consistent set of axioms. There does not seem to be any straightforward and intuitive mathematical procedure for checking completeness and consistency. Inconsistencies occur when axioms result in two objects being equivalent when in fact they should have been different. A complete axiom set is one to which an independent axiom cannot be added. A more thorough discussion of completeness and consistency can be found in [GUTTJ80].

Operations in algebraic specifications are all functions. They do not permit side effects and they can return only a single type of value. In addition, there are problems with partial operations and error equations ([MAJSM79]). The problem with errors occurs because an error is not of the

value type produced by an operation yet it may be the value produced by an operation. This can lead to contradictions. Goguen ([GOGUJ78]) and Guttag ([GUTTJ77]) have suggested solutions to these problems.

Verifying implementation correctness using a constructive specification method is conceptually easier than verifying implementation correctness using algebraic specifications. Flon ([FLONL79]) describes why this is the case. Algebraic methods deal with values rather than objects. Values are immutable; that is, an operation can change one value into another but it cannot change the state of a particular value. This means that operations cannot have side effects although in a typical procedural implementation operations have side effects. For instance, in an implementation of pop and push, these stack operations will not result in new stacks but rather will alter existing stacks. Constructive specification methods do not suffer from this problem since operations specified constructively deal with changing the state of objects.

A proof of implementation correctness must be done for each operation in a constructive specification whereas for algebraic specifications we must show that an implementation satisfies each axiom. For some data types, the number of axioms may be much larger that the number of operations. From our experience, there is nothing to suggest showing that an axiom is satisfied by an implementation is any easier than showing that an implementation of an operation is correct with respect to a homorphism. This suggests that the effort required to prove implementation correctness may be substantially larger for the algebraic approach than for the constructive approach. If one of the operations is changed then all of the axioms referring to the corresponding operation will have to be reverified.

In general, we have found that designing abstractions using constructive methods is much easier than the algebraic specification method. Minor changes in the behavior of an operation are easier to describe for constructive specifications. A modification in the definition of one constructively

defined operation does not normally affect the other operations. In an algebraic specification the meanings of the operations are defined in terms of the relations between them, so that a change in an operation or change in an axiom can affect other operations and axioms. It is difficult to produce a well-formed algebraic specification for a new data abstraction especially if the exact behavior required is not yet completely designed.

A major complaint against constructive specification methods is that they are not minimal, i.e. they introduce unnecessary detail. Proponents of the constructive methods argue that only those properties that are necessary and relevant to specifying semantics are specified. Auxiliary operations required by the algebraic method to specify some data abstractions such as the database view in Figure 10 can be considered to be unnecessary detail.

Another complaint against constructive specifications is that they suggest implementations and/or constrain the concrete objects. Berzins ([BERZV79]) states that the issues of time and space efficiency often requires that the representation used in an implementation differ significantly from the model used in the specification of semantics. One problem inherent in a constructive specification method is that specifying the semantics of complex operations may be quite lengthy. Constructive specifications sometimes lack the succinctness found in algebraic specifications.

In general, we have found constructive specifications easier for the user of a type to interpret. They permit an implementation to be more easily developed.

From our discussion above, it appears that constructive and algebraic approaches are ideally suited for some applications and poorly suited for others. Unfortunately, little attention has been devoted to the problems that occur when one tries to integrate the kind of examples occurring in the literature into real software written in real programming languages. The examples used in published reports have been well known mathematical objects.

These objects are familiar to most, thus it is difficult to demonstrate the value of specifying the semantics of operations, especially for communication purposes or in designing data abstractions. The database view example in this paper and in [CLAYB81a], [CLAYB81b] is an attempt to illustrate the importance of specifications in a practical situation. What has been missing in the literature are examples that provide user oriented operations on non-mathematical objects.

References

BERZV79 Berzins, Valdis, A. "Abstract Model Specifications for Data Abstractions", Ph.D. Thesis, MIT (MIR/LCS/TR-221).

CLAYB79 Claybrook, Billy G., et al. "Logical Structure and Data Type Definition", Proceedings of ACM 79 Conference, October 1979, pp. 203-211.

CLAYB80 Claybrook, Billy G. and Wyckoff, Marvin P. "module: An Encapsulation Mechanism for Specifying and Implementing Abstract Data Types", Proceedings of the ACM Annual Conference, October 1980, pp. 225-235.

CLAYB81a Claybrook, Billy G. "Data Abstraction in EXT Pascal", Sperry Research Center Research Paper SRC-RP-80-73, January 1981.

CLAYB81b Claybrook, Billy G. et al. "Defining Database Views as Data Abstractions", Sperry Research Center Research Paper TM 55-3, February 1981.

DATEC77 Date, C. J. An Introduction to Database Systems, Addison-Wesley, 1977.

GOGUJ78 Goguen, Josepn A., et al. "An Initial Algebra Approach to the Specification, Correctness, and Implementation of Abstract Data Types", Current Trends in Programming Methodology, Vol. 4, Data Structuring, R. Yeh (ed.), Prentice Hall, 1978, pp. 80-149.

GUTTJ75 Guttag, Jonn V. "The Specification and Application to Programming of Abstract Data Types", Ph.D. Thesis, Department of Computer Science, University of Toronto, Technical Report CSRG-59, 1975.

GUTTJ77 Guttag, John V., et al. Some Extensions to Algebraic Specifications", Proceedings of ACM Conference on Language Design for Reliable Software", SIGPLAN Notices, Vol. 12, March 1977, pp. 63-67.

GUTTJ78 Guttag, Jonn V. et al. "Abstract Data Types and Software Validation", CACM, Vol. 21, December 1978, pp. 1048-1064.

GUTTJ80 Guttag, John V. "Notes on Type Abstraction (Version 2)", IEEE Transactions on Software Engineering, Vol. SE-6, January 1980, pp. 13-23.

HOARA72 Hoare, C. A. R. "Proof of Correctness of Data Representations", Acta Informatica, 1, 4, 1972, pp. 271-281.

MAJSM79 Majster, Mila E. "Treatment of Partial Operations in the Algebraic Specification Technique", Proceedings of Specifications of Reliable Software Conference , April 1979, pp. 190-197.

MUSSD79 Musser, David. "Abstract Data Type Specification in the AFFIRM System", Proceedings of Specifications of Reliable Software Conference, April 1979, pp. 47-57.

ROWEL79 Rowe, Lawrence A. and Shoens, Kurt A. "Data Abstraction, Views and Updates in RIGEL", Proceedings of 1979 ACM SIGMOD Conference, Boston, May-June, 1979, pp. 71-81.

TAYLR76 Taylor, Robert W. and Frank, Randall L. "CODASYL Data-Base Management Systems", ACM Computing Surveys, Vol. 8, March 1976, pp. 67-103.

WULFW76 Wulf, William, et al. "An Introduction to the Construction and Verification of Alphard Programs", IEEE Transactions on Software Engineering, SE-2, 2, 4, December 1976, pp. 253-265.

WYCKM80 Wyckoff, Marvin P. "A Comparison of a Constructive and a Non-Constructive Approach to Data Type Specification", Masters Thesis, University of South Carolina, June 1980.

ZILLS79 Zilles, Stephen N. "An Introduction to Data Algebras", Lecture Notes in Computer Science, G. Goos and J. Hartmanis (eds.), Abstract Software Specifications, Springer-Verlay, New York, 1980, pp. 248-272.

Publications

"module: An Encapsulation Mechanism for Specifying and Implementing Abstract Data Types", Proceedings of the ACM Annual Conference, October 1980, pp. 225-235.

"Abstractly Identical Terms of An Abstract Data Type", Sperry Research Center Report RP-81-9 (submitted to TOPLAS).

"Language Extensions for Specifying Access Control Policies in Programming Languages", Sperry Research Center Report RP-80-74 (submitted to IEEE Transactions on Software Engineering).

"A Comparison of Two Specification Methods" (in preparation).

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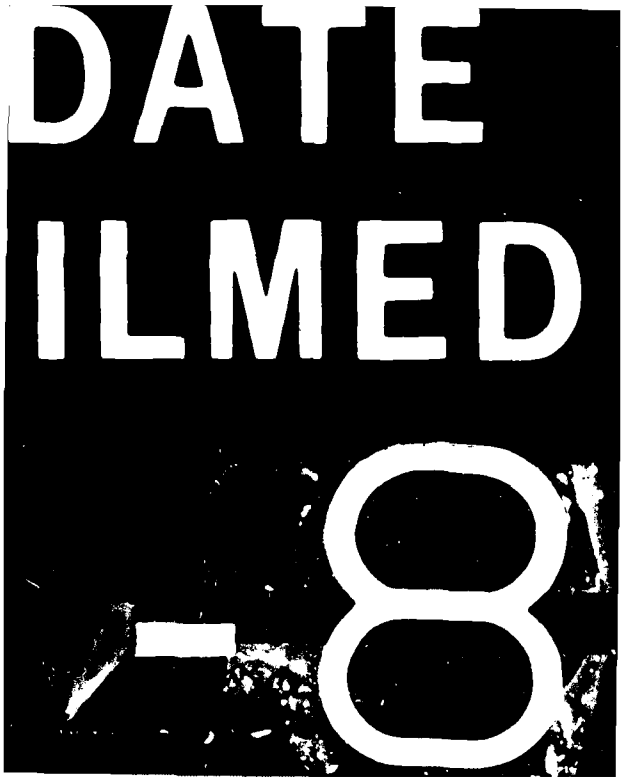
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